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Coherently enhanced wireless power transfer: theory and experiment

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Abstract. Extraction of electromagnetic energy by an antenna to a coupled waveguide is the crucial part of wireless power transfer. Efficiency of this process is usually defined by the coupling strength between the antenna and the outcoupling waveguide or cable. We show that there is an additional possibility to improve the receiving efficiency by coherent excitation of the outcoupling waveguide by a backward propagating guided mode with a specific amplitude and phase. This additional wave creates a special interference picture in the system and result in increased amount of energy extracted to the waveguide from the free space. We develop a simple analytical model predicting this effect, demonstrate it in numerical FDTD simulations, and verify in microwave experiment.

1. Introduction

An antenna is one of the most important elements in wireless technology, including communications and power transfer [1]. The first antennas were invented at the time of the discovery of electromagnetic waves by H. Hertz in 1888 and, since then, this technology has been progressing continuously. Nowadays, various types of antennas are commonly used for radio, microwave, THz and optical frequencies, where they have become irreplaceable elements for quantum optics and interconnections on a chip [2, 3]. While wireless communications are well established, wireless power transfer (WPT), proposed in the beginning of 20th century by N. Tesla [4], has been experiencing a rebirth in recent years, caused by demonstrations that the WPT efficiency, i.e., the ratio of energy received by an antenna over the total amount of emitted energy, can be drastically enhanced in the so-called near-field WPT regime, when the power is transferred via resonant coupling [5].

In this work, we introduce a conceptually different approach to realize robust WPT systems, relying on the local control of the wave impedance offered by interference phenomena. Specifically, we demonstrate that there is a possibility to improve the receiving efficiency of an antenna by *coherent excitation* of the outcoupling waveguide with a backward propagating signal of specific amplitude and phase, Fig. 1. This signal creates a specific interference pattern in the system that results in optimal wave impedance at the feed location, maximizing the energy transferred to the receiving antenna from free space. We develop an illustrative analytical model

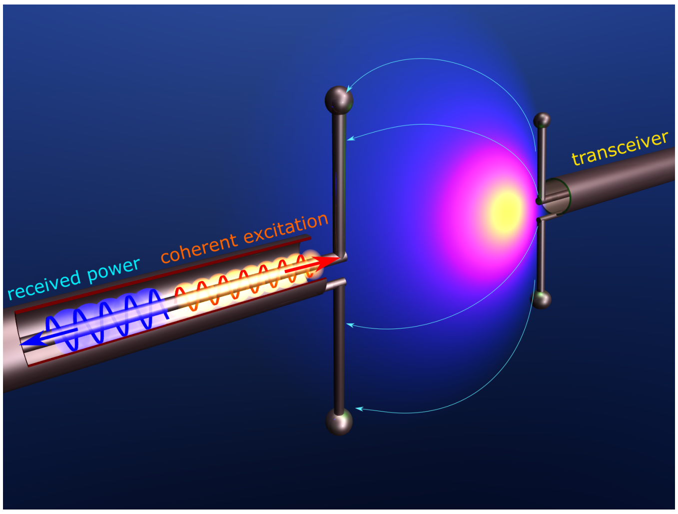

Figure 1. A schematic of coherently enhanced wireless energy transfer. The incident radiation of transceiver excites the antenna, which couples to waveguide creating a forward-propagating waveguide mode. Coherent excitation of the outcoupling waveguide with a backward propagating guided mode with specific amplitude and phase can retune the matching condition and largely improve the WPT performance.

predicting this effect, demonstrate it in full-wave numerical simulations, and in a microwave experiment.

2. Theoretical model

To demonstrate the effect of enhancing WPT's efficiency, we develop a theoretical model on the basis of temporal coupled mode theory [6, 7], which can be applied for both near-field and far-field WPT systems. The system of a waveguide-coupled antenna is schematically presented in Fig. 1. The dipole antenna is excited by an external field s_F created by a transceiver, which can be either free-propagating or evanescent. The antenna couples to a waveguide with amplitude $s_{\rm w}^-$, which carries the out-coupled energy to the receiver. To model the structure, we will assume that the antenna has a single resonance at the operating frequency ω_0. Moreover, for the sake of simplicity, we reduce the direct scattering matrix,which reflects the direct pathway between input and output channels, to a scalar c, assuming that the coupling of the antenna with free-space modes leading to additional radiation losses is taken into account by τ_F. The resulting amplitude of reflected mode that carries the transferred energy can be calculated via following equation:

$$s_{\rm w}^- = cs_{\rm w}^+ + \kappa_{\rm w}\frac{\kappa_{\rm w}s_{\rm w}^+ + \kappa_F s_F}{i(\omega-\omega_0)+1/\tau}. \quad (1)$$

where $s_{\rm w}^+$ is the amplitude of the input mode, τ is the mode damping time, $\kappa_{\rm w} = \sqrt{2/\tau_{\rm w}}$ and $\kappa_F = \sqrt{2/\tau_F}$, $\tau_{\rm w}$ is the antenna decay time into the waveguide mode, τ_F is the antenna decay time into radiation in free space. In order to study this dependence we plot the *energy balance* in transferred energy [Fig. 2(a)], defined as the total received energy $|s_{\rm w}^-|^2$ minus the energy spent in the auxiliary signal $|s_{\rm w}^+|^2$ that is sent from the waveguide port to the load, as a function of the auxiliary power $|s_{\rm w}^+|^2$ for different values of the relative phase $\varphi = Arg(s_{\rm w}^+/s_F)$. The shaded region marks all achievable values of the energy balance for phase from 0 to 2π, indicating that for a suitable combination of phase and amplitude it is possible to achieve perfectly matched regime, even after subtracting the energy carried by the back-propagating signal. In particular,

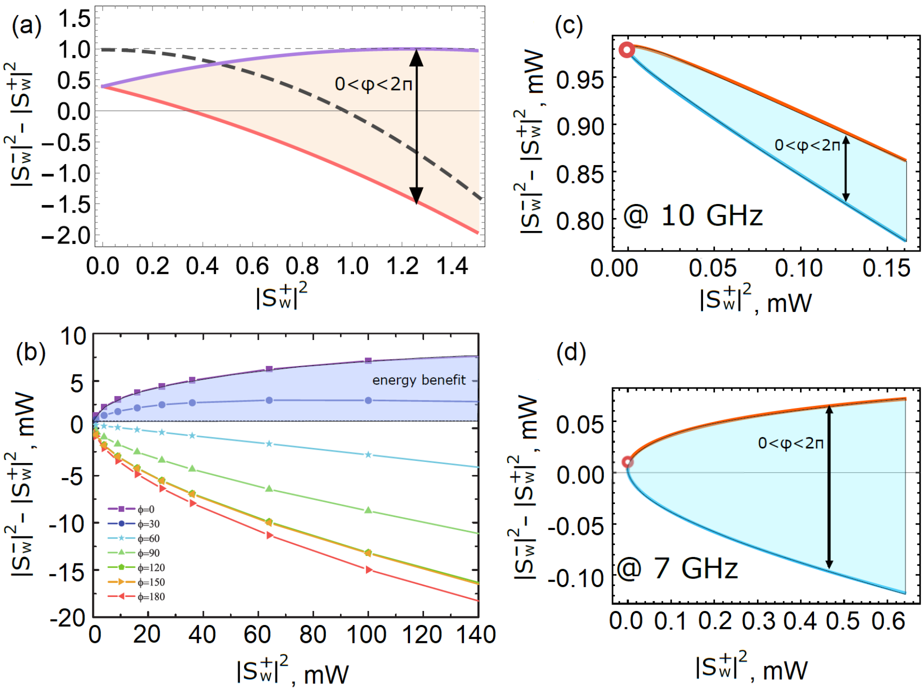

Figure 2. (a) Analytically calculated energy balance for a resonant matched (gray dashed curve) and resonant mismatched antenna (color solid curves). (b) Numerical calculations of energy balance as a function of the auxiliary signal intensity for different relative phase values. (c,d) The net extracted energy $|s_\mathrm{w}^-|^2 - |s_\mathrm{w}^+|^2$ vs power of the additional signal $|s_\mathrm{w}^+|^2$ for two different frequencies. The shaded area corresponds to all values of the relative phase between the external (default or main) signal and the auxiliary mode. The power of 1 mW is fed to port 1 in both cases.

for a certain phase difference the amount of extracted power (purple curve) reaches the ideal value of a resonant critically coupled antenna.

3. Numerical simulations and experiment

To verify the predictions of the analytical model, we carried out FDTD simulations of coherently enhanced outcoupling by using the CST Microwace Studio. In simulation, a coaxial cable was coupled to a non-resonant dipole antenna with 5 cm arm-length, which is excited by microwave radiation from the open end of a rectangular waveguide at 1.36 GHz. A distance between the antenna and the rectangular waveguide is about 40 cm. The results obtained by numerical calculation are shown in Fig. 2(b) and confirm the theoretical predictions. We note that the relative phase denoted here as ϕ is calculated for the Arg(s_w^+) and Arg(s_F) taken at different points (at the dipole antenna center and at the rectangular waveguide end, respectively) and, hence, depends on their relative distance. We would like to note here that the value s_F we used is a constant. However, when the coupling between the transmitter and receiver is sufficient, the coherent wave s_w^+ may influence on the matching conditions of the system transmitting antenna-its transmission line. It would lead to decreasing of s_F and therefore to decreasing of s_w^- and WPT efficiency.

Finally, we experimentally verified this concept by using a microwave two-port system. Each coaxial cable is connected to a vector network analyzer and terminated with a waveguide to coaxial adapter (WCA) that transforms electrical currents to propagating electromagnetic radiation. The cutoff frequency of WCAs is around 8 GHz, which manifests itself in high reflection (s_{11}) at frequencies below 8 GHz. Thus, the WCA operates as a mismatched antenna for frequencies below 8 GHz and an almost matched antenna for frequencies above 8 GHz. The port 1 creates free space radiation s_F, a part of which (s_w^-) then receives by port 2. The port 2 is excited by the auxiliary signal (s_w^+) of variable amplitude and phase. The resulting s-parameter spectra allow to observe coherently enhanced energy transfer. The dependence of the net extracted energy $|s_w^-|^2 - |s_w^+|^2$ versus power of the additional excitation $|s_w^+|^2$ for the whole set of relative phases $0 < \phi < 2\pi$ presented in Fig. 2(c) and (d) highlights the different behavior of the system in various spectral regions. At 10 GHz, where reflection by each WCA back to the coaxial cable is very low, excitation with the auxiliary signal barely improves the energy transfer. At 7 GHz, however, the situation is strikingly different: high reflection by the WCA enables order of magnitude enhancement of the transferred power, Fig. 2(d). This enhancement becomes possible due to a small transmission from port 1 to port 2 even at 7 GHz, which can be increased by interference with the auxiliary signal.

4. Conclusion

In conclusion, we have shown that coherent signals sent from the receiving port of a WPT system can largely enhance and control the power transfer efficiency. This additional signal creates a tailored interference in the system, modifying the local wave impedance at the antenna load, thus enabling conjugate matching and critical coupling even if the antenna itself is largely mismatched, resulting in increased amount of energy extracted to the waveguide from free space. We have developed an illustrative analytical model predicting this effect and demonstrated it in numerical simulations and in a microwave experiment. Our approach of coherently enhanced WPT can be applied for the development of efficient wireless power transfer systems with robust operation in rapidly changing environments, as common in practical situations and setups.

5. Acknowledgements

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